Claims

1. A process for conducting an equilibrium limited chemical reaction to convert a reactant composition to a desired product, the reactant composition comprising a primary reactant, the process comprising:

(A) determining the equilibrium conversion value for the primary reactant in the reactant composition at a first reaction temperature and at another reaction temperature;

(B) flowing the reactant composition through a first reaction zone in a microchannel reactor at the first reaction temperature in contact with a first catalyst to form an intermediate product composition, the intermediate product composition comprising the primary reactant and the desired product, the approach to equilibrium for conversion of the primary reactant in the first reaction zone being at least about 5%, and exchanging heat between the first reaction zone and a heat exchanger to maintain the temperature within the first reaction zone at the first reaction temperature; and

(C) flowing the intermediate product composition from the previous step through another reaction zone in the microchannel reactor at the another reaction temperature in contact with another catalyst to form the desired product, the approach to equilibrium for conversion of the primary reactant in the another reaction zone being at least about 5%; and exchanging heat between the another reaction zone and the heat exchanger to maintain the temperature within the another reaction zone at the another reaction temperature.

2. The process of claim 1 wherein the equilibrium conversion value for the primary reactant in the reactant composition at an additional reaction temperature between the first reaction temperature and the another reaction temperature is determined, and subsequent to step (B) but prior to step (C) the intermediate product composition formed in step (B) flows through an additional reaction zone in the microchannel reactor at the additional reaction temperature in contact with an additional catalyst to form another intermediate product composition, the another intermediate product composition comprising the primary reactant and the desired product, the approach to equilibrium for the conversion of the primary

reactant in the additional reaction zone being at least about 5%; and exchanging heat between the additional reaction zone and the heat exchanger to maintain the temperature within additional reaction zone at the additional reaction temperature.

3. The process of claim 1 wherein the approach to equilibrium for the conversion of the primary reactant in the first reaction zone, and the approach to equilibrium for the primary reactant in the another reaction zone are about the same.

4. The process of claim 2 wherein the approach to equilibrium for the conversion of the primary reactant in the first reaction zone, the approach to equilibrium for the conversion of the primary reactant in the another reaction zone, and the approach to equilibrium for the conversion of the primary reactant in the additional reaction zone are about the same.

5. The process of claim 1 wherein prior to the intermediate product composition entering the another reaction zone, the temperature of the intermediate product composition is changed from the first reaction temperature to the another reaction temperature.

6. The process of claim 2 wherein prior to the intermediate product composition entering the additional reaction zone, the temperature of the intermediate product composition is changed from the first reaction temperature to the additional reaction temperature.

7. The process of claim 1 wherein the equilibrium limited chemical reaction is an exothermic reaction.

8. The process of claim 1 wherein the another reaction temperature in step (C) is lower than the first reaction temperature in step (B).

9. The process of claim 2 wherein the additional reaction temperature is higher than the another reaction temperature in step (C) and lower than the first reaction temperature in step (B).

10. The process of claim 1 wherein the equilibrium limited chemical reaction is an endothermic reaction.

11. The process of claim 1 wherein the another reaction temperature in step (C) is higher than the first reaction temperature in step (B).

12. The process of claim 2 wherein the additional reaction temperature is lower than the another reaction temperature in step (C) and higher than the first reaction temperature in step (B).

13. The process of claim 1 wherein the first catalyst in step (B) is the same as the another catalyst in step (C).

14. The process of claim 2 wherein the additional catalyst is the same as the first catalyst in step (B), the another catalyst in step (C), or both the first catalyst in step (B) and the another catalyst in step (C).

15. The process of claim 1 wherein the first catalyst in step (B) is different than the another catalyst in step (C).

16. The process of claim 2 wherein the additional catalyst is different than the first catalyst in step (B), the another catalyst in step (C), or both the first catalyst in step (B) and the another catalyst in step (C).

17. The process of claim 1 wherein the microchannel reactor comprises a plurality of process microchannels.

18. The process of claim 17 wherein the process microchannels have internal dimensions of width or height of up to about 10 mm.

19. The process of claim 17 wherein the process microchannels are made of a material comprising: steel; monel; inconel; aluminum; titanium; nickel; copper; brass; an alloy of any of the foregoing metals; a polymer; ceramics; glass; a

composite comprising a polymer and fiberglass; quartz; silicon; or a combination of two or more thereof.

20. The process of claim 17 wherein the heat exchanger comprises at least one heat exchange channel adjacent to at least one process microchannel.

21. The process of claim 20 wherein the heat exchange channel comprises a microchannel.

22. The process of claim 21 wherein the heat exchange microchannel has an internal dimension of width or height of up to about 10 mm.

23. The process of claim 17 wherein the heat exchanger comprises at least one heat exchange channel adjacent to at least one process microchannel, the process microchannel having fluid flowing through it in one direction, the heat exchange channel having fluid flow through it in a direction that is counter-current to the flow of fluid through the process microchannel.

24. The process of claim 17 wherein the heat exchanger comprises at least one heat exchange adjacent to at least one process microchannel, the process microchannel having a fluid flowing through it in one direction, the heat exchange channel having fluid flow through it in a direction that is co-current to the flow of fluid through the process microchannel.

25. The process of claim 17 wherein the heat exchanger comprises a plurality of heat exchange channels adjacent to at least one process microchannel, the process microchannel having fluid flowing through it in one direction, the heat exchange channels having fluid flowing through them in a direction that is cross-current to the flow of fluids through the process microchannel.

26. The process of claim 17 wherein at least one process microchannel has an adjacent heat exchange channel, the length of the process microchannel and the length of the heat exchange channel being the same.

27. The process of claim 17 wherein at least one process microchannel has an adjacent heat exchange channel, the process microchannel having an entrance and an exit, the heat exchange channel extending lengthwise in the same direction as the process microchannel, the length of the heat exchange channel being shorter than the length of the process microchannel, the heat exchange channel being positioned at or near the process microchannel exit.

28. The process of claim 17 wherein the heat exchanger comprises a heat exchange zone adjacent to at least one process microchannel, the heat exchange zone comprising a plurality of heat exchange channels, the process microchannel having an entrance and an exit, the heat exchange channels extending lengthwise at a right angle relative to the lengthwise direction of the process microchannel, the heat exchange zone extending lengthwise in the same direction as the process microchannel, the length of the heat exchange zone being shorter than the length of the process microchannel, the heat exchange zone being positioned at or near the process microchannel exit.

29. The process of claim 17 wherein the heat exchanger comprises two heat exchange zones adjacent to at least one process microchannel, each heat exchange zone comprising a plurality of heat exchange channels, the heat exchange channels extending lengthwise at a right angle relative to the lengthwise direction of the process microchannel, the process microchannel having an entrance and an exit, the heat exchange zones extending lengthwise in the same direction as the process microchannel, the lengths of the heat exchange zones being shorter than the length of the process microchannel, the length of one of the heat exchange zones being shorter than the length of the other heat exchange zone, the heat exchange zones being positioned at or near the process microchannel exit.

30. The process of claim 20 wherein the heat exchange channel is made of a material comprising: steel; monel; inconel; aluminum; titanium; nickel; copper; brass; an alloy of any of the foregoing metals; a polymer; ceramics; glass; a

composite comprising polymer and fiberglass; quartz; silicon; or a combination of two or more thereof.

31. The process of claim 20 wherein the process microchannel exchanges heat with a heat exchange fluid flowing through the heat exchange channel.

32. The process of claim 31 wherein the heat exchange fluid undergoes a phase change as it flows through the heat exchange channel.

33. The process of claim 20 wherein an endothermic process is conducted in the heat exchange channel.

34. The process of claim 33 wherein the endothermic process comprises a steam reforming reaction or a dehydrogenation reaction.

35. The process of claim 31 wherein the heat exchange fluid comprises air, steam, liquid water, carbon dioxide, gaseous nitrogen, a gaseous hydrocarbon or a liquid hydrocarbon.

36. The process of claim 1 wherein the first catalyst, the another catalyst, or both the first catalyst and the another catalyst are in the form of particulate solids.

37. The process of claim 17 wherein the first catalyst, the another catalyst, or both the first catalyst and the another catalyst are washcoated on interior walls of the process microchannels, grown on interior walls of the process microchannels from solution, or coated in situ on a fin structure.

38. The process of claim 1 wherein the first catalyst, the another catalyst, or both the first catalyst and the another catalyst are supported by a support structure made of a material comprising an alloy comprising Ni, Cr and Fe, or an alloy comprising Fe, Cr, Al and Y.

39. The process of claim 1 wherein the first catalyst, the another catalyst, or both the first catalyst and the another catalyst are supported on a support structure having a flow-by configuration, a flow-through configuration, or a serpentine configuration.

40. The process of claim 1 wherein the first catalyst, the another catalyst, or both the first catalyst and the another catalyst are supported on a support structure having the configuration of a foam, felt, wad, fin, or a combination of two or more thereof.

41. The process of claim 1 wherein the first catalyst, the another catalyst, or both the first catalyst and the another catalyst are supported on a support structure having a flow-by configuration with an adjacent gap, a foam configuration with an adjacent gap, a fin structure with gaps, a washcoat on a substrate, or a gauze configuration with a gap for flow.

42. The process of claim 1 wherein the first catalyst, the another catalyst, or both the first catalyst and the another catalyst are supported on a support structure in the form of a fin assembly comprising at least one fin

43. The process of claim 42 wherein the fin assembly comprises a plurality of parallel spaced fins.

44. The process of claim 42 wherein the fin has an exterior surface and a porous material overlies at least part of the exterior surface of the fin, the catalyst being supported by the porous material.

45. The process of claim 44 wherein the porous material comprises a coating, fibers, foam or felt.

46. The process of claim 42 wherein the fin has an exterior surface and a plurality fibers or protrusions extend from at least part of the exterior surface of the fin, the catalyst being supported by the protrusions.

47. The process of claim 42 wherein the fin has an exterior surface and the catalyst is: washcoated on at least part of the exterior surface of the fin; grown on at least part of the exterior surface of the fin from solution; or deposited on at least part of the exterior surface of the fin using vapor deposition.

48. The process of claim 42 wherein the fin assembly comprises a plurality of parallel spaced fins, at least one of the fins having a length that is different than the length of the other fins.

49. The process of claim 42 wherein the fin assembly comprises a plurality of parallel spaced fins, at least one of the fins having a height that is different than the height of the other fins.

50. The process of claim 42 wherein the fin has a cross section having the shape of a square, a rectangle, or a trapezoid.

51. The process of claim 42 wherein the fin is made of a material comprising: steel; aluminum; titanium; iron; nickel; platinum; rhodium; copper; chromium; brass; an alloy of any of the foregoing metals; a polymer; ceramics; glass; a composite comprising polymer and fiberglass; quartz; silicon; or a combination of two or more thereof.

52. The process of claim 42 wherein the fin is made of an alloy comprising Ni, Cr and Fe, or an alloy comprising Fe, Cr, Al and Y.

53. The process of claim 42 wherein the fin is made of an Al_2O_3 forming material or a Cr_2O_3 forming material.

54. The process of claim 17 wherein the process microchannels have a bulk flow path comprising about 5% to about 95% of the cross sections of such process microchannels.

55. The process of claim 1 wherein the equilibrium limited chemical reaction is a methanol synthesis reaction.

56. The process of claim 1 wherein the equilibrium limited chemical reaction is a dimethyl ether synthesis reaction.

57. The process of claim 1 wherein the equilibrium limited chemical reaction is a methanol synthesis reaction, dimethyl ether synthesis reaction, ammonia synthesis reaction, water gas shift reaction, acetylation addition reaction, alkylation, dealkylation, hydrodealkylation, reductive alkylation, amination, aromatization, arylation, autothermal reforming, carbonylation, decarbonylation, reductive carbonylation, carboxylation, reductive carboxylation, reductive coupling, condensation, cracking, hydrocracking, cyclization, cyclooligomerization, dehalogenation, dimerization, epoxidation, esterification, Fischer-Tropsch reaction, halogenation, hydrohalogenation, homologation, hydration, dehydration, hydrogenation, dehydrogenation, hydrocarboxylation, hydroformylation, hydrogenolysis, hydrometallation, hydrosilation, hydrolysis, hydrotreating, isomerization, methylation, demethylation, metathesis, nitration, oxidation, partial oxidation, polymerization, reduction, reformation, reverse water gas shift, sulfonation, telomerization, transesterification, trimerization, Sabatier reaction, carbon dioxide reforming, preferential oxidation, or preferential methanation.

58. The process of claim 1 wherein the reactant composition comprises H_2 and CO.

59. The process of claim 58 wherein the reactant composition further comprises H_2O, CO_2, N_2, a hydrocarbon of 1 to about 4 carbon atoms, or a mixture of two or more thereof.

60. The process of claim 1 wherein the contact time of the reactant composition and/or intermediate product composition with the catalyst in the first reaction zone is from about 10 to about 400 milliseconds.

61. The process of claim 1 wherein the contact time of the intermediate product composition and/or product with the catalyst in the another reaction zone is from about 10 to about 400 milliseconds.

62. The process of claim 1 wherein the temperature of the reactant composition entering the process microchannels is in the range of about 25°C to about 800°C.

63. The process of claim 1 wherein the temperature within the first reaction zone is from about 25°C to about 800°C.

64. The process of claim 1 wherein the temperature within the another reaction zone is from about 100°C to about 800°C.

65. The process of claim 1 wherein the pressure within the process microchannels is at least about 1 atmosphere.

66. The process of claim 1 wherein the pressure drop for the flow of the reactant composition and product through the process microchannels is up to about 40 atmospheres per meter of length of the process microchannels.

67. The process of claim 20 wherein a heat exchange fluid flows through the heat exchange channel, the pressure drop for the heat exchange fluid flowing through the heat exchange channel being up to about 50 atmospheres per meter of length of the heat exchange channel.

68. The process of claim 1 wherein the microchannel reactor has an entrance and an exit, the product exits the microchannel reactor through the exit, the product being intermixed with unreacted reactants from the reactant composition, and at least part of the unreacted reactants from the reactant composition being recycled to the entrance to the microchannel reactor.

69. A process for conducting an equilibrium limited chemical reaction to convert a reactant composition to a desired product, the reactant composition comprising a primary reactant, the process comprising:

(A) determining the equilibrium conversion value for the primary reactant in the reactant composition at a first reaction temperature and at another reaction temperature;

(B) flowing the reactant composition through a first reaction zone in a microchannel reactor at the first reaction temperature in contact with a first catalyst to form an intermediate product composition, the intermediate product composition comprising the primary reactant and the desired product, the approach to equilibrium for conversion of the primary reactant in the first reaction zone being at least about 40%, and exchanging heat between the first reaction zone and a heat exchanger to maintain the temperature within the first reaction zone at the first reaction temperature; and

(C) flowing the intermediate product composition from the previous step through another reaction zone in the microchannel reactor at the another reaction temperature in contact with another catalyst to form the desired product, the approach to equilibrium for conversion of the primary reactant in the another reaction zone being at least about 40%; and exchanging heat between the another reaction zone and the heat exchanger to maintain the temperature within the another reaction zone at the another reaction temperature.

70. The process of claim 69 wherein the approach to equilibrium for the conversion of the primary reactant in the first reaction zone and in the another reaction zone is independently at least about 50%.

71. The process of claim 69 wherein the approach to equilibrium for the conversion of the primary reactant in the first reaction zone and in the another reaction zone is independently at least about 70%.

72. The process of claim 69 wherein the approach to equilibrium for the conversion of the primary reactant in the first reaction zone and in the another reaction zone is independently from about 75% to about 95%.

73. A process for conducting a methanol synthesis reaction to convert a reactant composition comprising a primary reactant to CH_3OH, the process comprising:

(A) determining the equilibrium conversion value for the primary reactant in the reactant composition at a first reaction temperature and at another reaction temperature;

(B) flowing the reactant composition through a first reaction zone in a microchannel reactor at the first reaction temperature in contact with a first catalyst to form an intermediate product composition, the intermediate product composition comprising the primary reactant and CH_3OH, the approach to equilibrium for the conversion of the primary reactant in the first reaction zone being from about 75% to about 95%; and exchanging heat between the first reaction zone and a heat exchanger to maintain the temperature within the first reaction zone at the first reaction temperature; and

(C) flowing the intermediate product composition from the previous step through another reaction zone in the microchannel reactor at the another reaction temperature in contact with another catalyst to form CH_3OH, the approach to equilibrium for the conversion of the primary reactant in the another reaction zone being from about 75% to about 95%; and exchanging heat between the another reaction zone and the heat exchanger to maintain the temperature within the another reaction zone at the another reaction temperature.

74. A process for conducting a dimethyl ether synthesis reaction to convert a reactant composition comprising CO and H_2 to dimethyl ether, the process comprising:

(A) determining the equilibrium conversion value for CO in the reactant composition at a first reaction temperature and at another reaction temperature;

(B) flowing the reactant composition through a first reaction zone in a microchannel reactor at the first reaction temperature in contact with a first catalyst to form an intermediate product composition, the intermediate product composition comprising CO, H_2, CO_2 and dimethyl ether, the approach to equilibrium for the conversion of CO in the first reaction zone being from about 75% to about 95%; and

exchanging heat between the first reaction zone and a heat exchanger to maintain the temperature within the first reaction zone at the first reaction temperature; and

(C) flowing the intermediate product composition from the previous step through another reaction zone in the microchannel reactor at the another reaction temperature in contact with another catalyst to form dimethyl ether and CO_2, the approach to equilibrium for the conversion of CO in the another reaction zone being from about 75% to about 95%; and exchanging heat between the another reaction zone and the heat exchanger to maintain the temperature within the another reaction zone at the another reaction temperature.